BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B69 10049

SUBJECT: Improved Lunar Landing Visibility Resulting from Greater Expected Relative Sun Azimuth for High Latitude Sites - Case 310

DATE: October 15, 1969

FROM: R. A. Bass

ABSTRACT

For conditions where the LM flight path angle is approximately equal to the sun's elevation, high latitude landing sites will have improved landing visibility over near-equatorial sites because of the greater relative azimuth between the LM approach path and the sun. Present lighting ground rules allow landings at sun elevations from 5 to 14 degrees, exclude the region from 14 to 18 degrees, and allow elevations from 18 to 20 degrees. With staytimes of 78 hours at sites more than ten degrees from the equator, trajectory optimization will normally yield relative sun azimuths such that the scene contrast for sun elevations of 14 to 18 degrees is better than for a twenty degree sun elevation at zero relative azimuth. Similar conclusions can be made for lunar staytimes of 32 hours to sites located more than 20 degrees from the equator but with less confidence, as more deviations from the rule can be expected.

The cost in propellant for forcing the approach azimuth off the optimum to improve visibility varies for different sites, launch dates and staytimes; and it is highly non-linear depending on the magnitude of the desired change. For a difficult site such as Tycho, the cost can be as high as 200 lbs/degree of azimuth change off the optimum.

In most cases landing sites at northern latitudes result in more favorable sunlight conditions for redesignation as the washout region will lie to the right of the flight path and away from the preferred redesignation area.

N79-71636

(NASA-CR-109077) IMPROVED LUNAR LANDING VISIBILITY RESULTING FROM GREATER EXPECTED RELATIVE SUN AZIMUTH FOR HIGH LATITUDE SITES (Bellcomm, Inc.) 27 p

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FF No. 602(A)

(PAGES) (CODE)

CR-109077

(NASA CR OR TMX OR AD NUMBER) (CATEGORY)

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MEMORANDUM FOR FILE

It has been shown in Reference 1 that pilot visibility during LM descent can be improved in situations where the sun line is near or above the LM approach flight path angle by approaching the landing site with a non-zero relative azimuth between the sun and the LM approach path. Scene contrast as a function of sun elevation and relative sun azimuth is shown in Figures 1, 2 and 3 for three LM approach flight paths. In these figures washout or zero contrast occurs when the sun elevation approaches the flight path angle with no relative sun azimuth. It is apparent from the curves that a non-zero relative sun azimuth, ΔA_Z, results in increased scene contrast.

This memorandum investigates optimum trajectories to Apollo lunar exploration sites to determine expected ranges of relative sun azimuth and the resultant effect on scene contrast. Propellant costs for controlling relative sun azimuth are also discussed.

SUN AZIMUTH

In the following discussion sun azimuth is defined as the angle, in the local horizontal plane, of the tangential component of the vector from the sun to the landing site measured clockwise from north. An equivalent definition is the angle between the shadow of a pole at the landing site and the local meridian measured clockwise from north. (See Figures 4 and 5). During a lunar cycle the sun azimuth at touchdown is defined by the site latitude and the sun elevation at arrival, neglecting the small effect of the 1-1/2 degree angle between the moon's equator and the ecliptic. Figure 6 shows sun azimuths for site latitudes from -50° to +50° and sun elevations from 5° to 60°. Sun azimuth is greater than -90° for northern sites and less than -90° for southern sites under a morning sun. Shadows will be cast away from the equator as shown in Figures 4 and 5. The largest change in azimuth (from -90 degrees) for the sites presently under consideration and sun elevation between 5° and 20° is -108.5° for Tycho (latitude of 41° south).

"EXPECTED" APPROACH AZIMUTH

The propellant-optimum approach azimuth to a lunar landing site is determined by the three major maneuvers; lunar orbit insertion (LOI), the CSM plane change maneuver (PCM) prior to rendezvous, and transearth injection (TEI). The maneuver most influential on total propellant usage is LOI, as spacecraft weight at that time is the highest since the LM is attached. Understanding the relationship between approach azimuth and both the LOI requirement and PCM requirement permits a first order estimate of the approach azimuth expected for a particular landing site.

The LOI Maneuver Influence

The ΔV at LOI is determined by the flight path angle change, the plane change and the energy change required to transfer from the incoming hyperbolic trajectory to the circular orbit. ΔV_{LOI} is at a minimum when the translunar energy is low (long translunar flight time) and when deboost to lunar orbit is made inplane at periselene. It is apparent that optimization would tend to select the lunar orbit orientation determined by the site location and approach azimuth that allows these conditions to exist.

Translunar trajectories may pass through a large area on the moon's sphere of influence (MSI) with a specific flight time and dihedral angle without materially affecting the energy of the hyperbolic approach trajectory or the seleocentric velocity direction at the MSI. Thus the hyperbolic excess velocity vector (velocity at infinity) is essentially constant for a specific flight time and a dihedral angle.

The angle, i_∞, that the hyperbolic excess velocity vector, V_∞, makes with the lunar orbit plane defines the minimum plane change possible at LOI. A good start in defining "expected" approach azimuth would be to determine the condition under which i_∞ will be minimized. Figure 8 taken from Reference 2 shows the location of the V_∞ on the MSI (where $-V_\infty$ would pierce the MSI) for various translunar flight times and dihedral angles for different conditions during the lunar cycle. Dihedral angle is not a free parameter as it is determined by the launch date and launch azimuth. Translunar flight time is available for optimization control in non-free return and hybrid missions. Hybrid missions have an upper bound on flight time because of the DPS abort constraint. Figure 8 shows that the V_∞ location is defined by an essentially constant latitude line about 40 degrees long whose median varies in latitude from 0 to $\pm$ 8 degrees as a function of dihedral angle and in longitude from 50 to 65 degrees depending on the position and velocity of the moon. The location of V_∞ along this line is fixed by the flight time.

Neglecting the difference between the selenographic equator and the earth-moon plane for a moment and placing a site and a possible lunar orbit on a mercator plot, the relation of i_∞ to the approach azimuth can be seen (Figure 9). Examining this relation in light of the previous observation that optimization would drive i_∞ to near zero, it is seen that there is a range of approach azimuths, paired with an appropriate translunar flight time, where i_∞ will be zero. This possible range of approach azimuth decreases with eastward movement of the landing site. Of all these possible azimuths where i_∞ is zero, the lowest ΔV_{LOI} will coincide with the longest flight time.

Sites located less than ninety degrees east of the western limit of the line of $\vec{V}_\infty$ locations (between 45°W and 10°E) will have azimuths that result in the LM approaching the equator at landing. For northern sites approach azimuths less than -90° and for southern sites azimuths greater than -90° will be the rule. Sites outside of this region will not follow the rule. Those west of 45°W can have azimuths where the CM will be moving away from the equator for short translunar flight times. Approach azimuths to sites east of 10°E will also result in the LM moving away from the equator but only for long flight times. The LM will be moving away from the equator for all landings east of 45°E.

The effect of the librations of the moon will cause the line of V_∞ MSI pierce points to move approximately $\pm 6.5°$ in both selenographic latitude and longitude in relation to a specific site. This movement will move the previously mentioned longitude limits (defining approach azimuth ranges) somewhat but does not change the general conclusions.

The Plane Change Maneuver Influence

The best approach azimuth for the PCM is obviously the one that eliminates the need for the maneuver; requiring no plane change prior to rendezvous. Examining Figure 7 it can be seen that for staytimes less than 14 days approach azimuths requiring no PCM will have the LM approaching the equator on landing. Fortunately this conclusion coincides with the one made concerning ΔV_{LOI} for the western region of the moon. The CSM ground track propagates across the moon relative to the landing site during the staytime and ascent occurs when the CSM passes over the site with the absolute value of the sub-vehicle point latitude now increasing. Here for convenience the landing site is shown moving relative to the ground trace during the lunar stay. If staytimes are greater than fourteen days, the preferred direction of approach will reverse as indicated in Figure 7b.

Approach azimuth at landing is plotted against flight azimuth at rendezvous as a function of site latitude in Figures 10 and 11 using a 32 and 78 hour staytime respectively. Rendezvous flight azimuths were calculated assuming the CSM plane change maneuver was made at the optimum location on the parking orbit, that is the position minimizing the magnitude of the plane change. Also noted in the figures is the CSM pre-rendezvous plane change (β) required, given the site latitude and the approach azimuth at landing.

The approach azimuth for no PCM at any latitude is defined by the $\beta = 0$ line. As noted before, approach azimuths are less than -90° for northern sites and greater than -90° for southern sites.

Figures 10 and 11 are divided into those combinations of approach azimuths and site latitudes that require plane change maneuvers that increase and those that decrease the lunar orbit inclination. This relationship is of interest in planning for post-rendezvous CSM photography where higher inclinations are desirable.

Neglecting TEI effects the no PCM approach azimuths are a good estimate of the optimum azimuth for sites in the west as the no PCM will probably lie in the band of possible azimuths where i_∞ will be zero. This will not hold true for eastern sites as a best azimuth for LOI and the best for PCM can differ widely and the true optimum will be somewhere between the two. The no PCM assumption is used to define "expected" relative sun azimuths as a majority of the lunar exploration sites now under consideration are west of 10° East longitude and are all west of 35° East longitude.

"EXPECTED" RELATIVE SUN AZIMUTHS

Since the sun azimuth has been defined as a function of site latitude and sun elevation (Figure 6) and approach azimuth is shown as a function of site latitude in Figures 10 and 11 (the β=0 line), the "expected" relative azimuth can be calculated for a specific latitude, sun elevation and staytime. Figure 12 shows "expected" ΔA_Z for a 78 hour stay time as a function of site latitude with sun elevation as a parameter. Figure 13 shows similar results for the 32 hour staytime.

As can be seen by these curves the "expected" ΔA_Z will be small for sites near the equator. As the site is chosen farther from the equator and the staytime is increased, ΔA_Z will increase.

COMPARISON OF "EXPECTED" ΔA_Z TO OPTIMIZATION RESULTS

The accuracy of the prediction of ΔA_Z is solely dependent on the approach azimuth at landing for the optimum mission to a particular site. The closer the optimum approach azimuth is to the "expected" azimuth (the one yielding no CSM plane change) the better the prediction accuracy.

For sites in the Apollo zone the approach azimuths relative to the sun are small. Examining twelve months of optimized free return trajectories to the five Apollo sites it was found that 90 percent of the time the relative azimuth was less than seven degrees; it was always less than twelve degrees.

Data for trajectory scans over a lunar cycle to a number of science sites under various translunar profiles were compared to the predicted ΔA_Z. Table I gives a comparison between the "expected" approach azimuth (no CSM plane change) and the actual range found for optimum trajectories (SPS propellant minimized) over a lunar cycle. The variation in optimum flight azimuth during a lunar cycle ranges from 10.4 to 22 degrees during a lunar cycle for the short staytime data with the average near 17°. The scans for the longer staytimes show variation ranges of 2° to 30°.

Using the approach azimuth range found for a lunar cycle performance scan in combination with the data in Figure 6 for a 5° to 20° sun elevation constraint, it is possible to determine the extremals of the ΔA_Z range that would actually occur during a lunar cycle. These ranges are listed in the last column of Table I and are also superimposed on Figures 12 or 13 according to the appropriate staytime and specific site latitude. Data is shown for Schroeter's Valley, Littrow and Tycho for 78 hour staytime and for Schroeter's Valley, Littrow, Abulfeda, Tobias Mayer Domes, Hygenus and Gassendi for 32 hour staytime.

Gassendi, Schroeter's Valley and Tobias Mayer Domes have optimum flight azimuths that yield greater relative sun azimuths than predicted through the use of the Figure 13 curves. Tycho and Schroeter's Valley optimum also reflect greater relative sun azimuths than predicted by Figure 12. The sites in the east, Abulfeda, Littrow and Hyginus, show less agreement; but much of the time, sufficient relative sun azimuth exists to avoid contrast washout.

Littrow shows the tradeoff that is made between the best approach azimuth for LOI and the best for PCM when optimizing missions to eastern sites. The no PCM azimuth for a 32 hour staytime is -93.7°. The best approach azimuth for Pacific injection* with no LOI plane change ranges from approximately -71° for long flight times to -101° for short flight times including the effects of lunar librations. Since ΔV_{LOI} for inplane maneuvers decreases for increased time of flight and PCM ΔV increases either side of -93.7°, the best azimuth would be between -93.7° and -71° neglecting TEI effects. Since the sun azimuth at this latitude ranges from -82° to -88° for 5° to 20° sun elevation, the relative sun azimuth can range from -17° to +11.7°. Atlantic injection tends to decrease the approach azimuth and thus increase the relative sun azimuth as the line of $\vec{V}_\infty$ location is located farther south as shown in Figure 8 (negative dihedral angles).

ΔA_Z variation over a lunar cycle for non-free return trajectory scans to Littrow, Tycho and Schroeter's Valley is presented in Figure 14. The data represents SPS propellant minimum missions found for each month, constraining the sun elevation at landing to lie between five and twelve degrees. Littrow shows poor agreement with the expected band as it lies in the east. Tycho and about half the Schroeter's Valley data shows excellent agreement. Schroeter's Valley located at 56° West lies directly above the line of V_∞ pierce points. The

*Pacific injection corresponds to positive inclinations to the moon's plane (dihedral angle) and Atlantic injection to negative as shown in Figure 8.

period where the optimum approach azimuths are less than expected, causing the high relative sun azimuths, coincides with the most southward movement of the region of V_∞ pierce points in the selenographic system. The no PCM azimuth of -100° is larger than the approach azimuth for $i_\infty=0$ associated with the longest reasonable time of translunar flight.

The influence of the PCM on the optimum will diminish as staytime is shortened as shown by a comparison of Figure 10 and 11 since sensitivity of propellant costs to azimuth change for the PCM maneuver decreases markedly.

CONTRAST IMPROVEMENT

A region is mapped out on the contrast-sun elevation curves of Figures 1 through 3 using the "expected" relative sun azimuth data shown in Figure 10 for a 78 hour staytime and sites located 10 to 40 degrees off the equator. Substantial contrast improvement is shown; contrast in the excluded band from 14 to 18 degrees is better than that obtained for the zero azimuth case in the acceptable 18 to 20 degree region.

LM REDESIGNATION

LM redesignation will probably be made to the left as visibility for the LM pilot is better in that direction. Thus, northern sites will usually be better for redesignation as the LM shadow and similarly the washout region will be to the right and away from the area being viewed by the pilot (Figure 4). The situation for southern sites is reversed and the LM shadow will appear on the left of the approaching LM (Figure 5).

PROPELLANT PENALTIES FOR OFF-OPTIMUM APPROACH AZIMUTHS

Propellant penalties (decrease in propellant reserve at the end of the mission with full tanks at launch) for approach paths off the optimum are dependent on the site latitude, longitude and staytime among other things. Under the J mission configuration Tycho shows a sensitivity of about 200 lbs. fuel/degree of azimuth change off the optimum. This sensitivity is good for ranges of $\pm$ 5° from the optimum approach azimuth. Larger deviations result in greater sensitivities.

	Sensitivity - Fuel at 5° from Optimum
Tycho (78 hour stay)	200 lbs/deg.
Schroeter's Valley (78 hour stay)	200 lbs/deg.
Littrow (30 hour stay)	90 lbs/deg.

A better perspective of the sensitivity of propellant costs to azimuth change is shown in Figures 15, 16 and 17 where the scan data is plotted in terms of fuel penalty versus azimuth variation from the optimum for these three sites. Each point on these plots represents an optimum mission for a particular month and approach azimuth under a constraint of landing when the sun elevation is between 5° and 12°. Propellant consumption and approach azimuth were both normalized to the optimum mission for the year. Littrow shows much less sensitivity to azimuth variations than either Tycho or Schroeter's Valley.

CONCLUSIONS

1. Relative sun azimuth can be expected to increase as landing sites move away from the equator. As a result the scene contrast and pilot visibility are improved during lunar landings for which the sun's elevation is near the LM flight path angle.

2. A blanket exclusion of the 14° to 18° sun elevation band from the acceptable region of lighting at landing should not be made for all lunar exploration missions as many sites will have optimum approach paths with large relative sun azimuths producing scene contrast equal to or better than the zero azimuth contrast in the 18 and 20 degree sun elevation range.

3. For short staytimes and/or for sites close to the equator where small relative azimuths occur, low propellant penalties for moving the approach azimuth off the optimum allow some flexibility to improve scene contrast.

4. Generally washout will appear off to the right of the LM pilot on an optimum approach to a northern site and off to the left for a southern site.

R.A. Bass

2013-RAB-srb R. A. Bass

Attachments:

REFERENCES

1. Anselmo, D. R., Cavedo, P. A., "Evaluation of Lunar Lighting Constraint Based Upon Photometric Derived Scene Contrast", Bellcomm Technical Memorandum TM-66-2013-1, April 29, 1966.

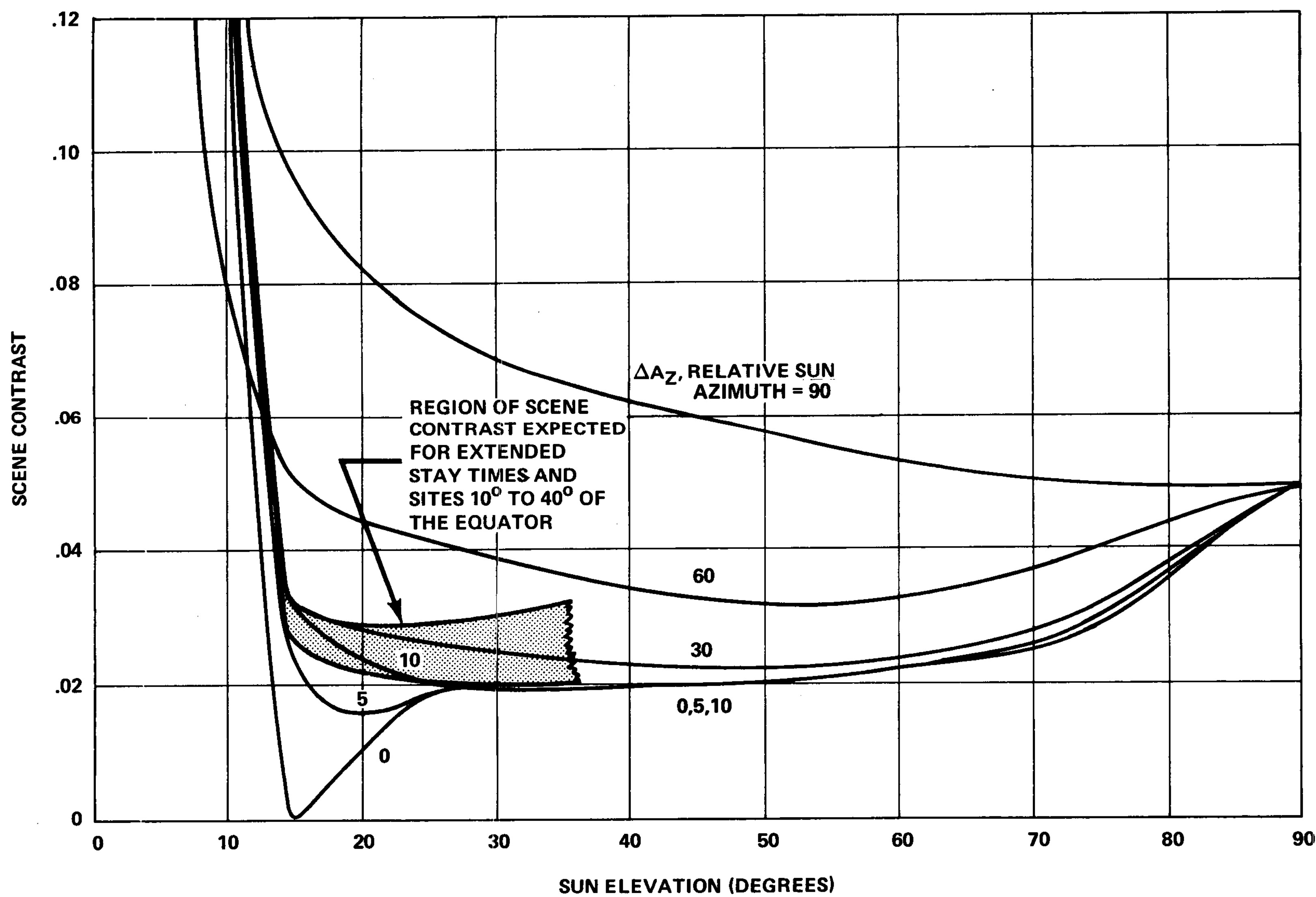
2. Apollo Mission Parameter Analysis - 8408-6050-RC-000, May 29, 1964. TRW Space Technology Laboratories.

TABLE :

OPTIMUM FLIGHT AZIMUTH VARIATION THROUGH A LUNAR CYCLE

SITE	SITE LATITUDE	AZIMUTH FOR NO CSM PLANE CHANGE	TRAJECTORY TYPE AND STAY TIME				ΔA_Z RANGE FOR SUN ELEVATION FROM 5° to 20°
			35 HOUR STAY TIME				
			NON-FREE RETURN WITH DPS ABORT		HYBRID*		
			ATLANTIC	PACIFIC	ATLANTIC	PACIFIC	
LITTROW	22°	-93.7°	-97 to -99.5	-73 to -94	-79.2 to -101.2	-73.7 to -94.2	-15 to +19
HYGINUS	8°	-91.3°	-85 to -104.1	-79.1 to -97.8	-85.2 to -102.7	-79.5 to -97.7	-10 to +17
GASSENDI	-19°	-87.8°	-66 to -86.5	-70.5 to -81	-67.0 to -86.5	-69.7 to -83.5	-5 to -31
SCHROETER'S VALLEY	26°	-94.2°			-98.5 to -112.5	-98.5 to -108.5	+11 to +33
TOBIAS MAYER DOMES	13°	-92.5°			-94.5 to -113.5	-94.5 to 108.5	+ 6 to +27
ABULFEDA	-15°	-85.0			-84.5 to -99.5	-80 to -91	-15.5 to + 7.5
			72 - 78 HOUR STAY TIME				
					HYBRID*		
			NON-FREE RETURN PACIFIC		ATLANTIC	PACIFIC	
TYCHO	-41°	-76°	-74° to -76°				-36 to -17
SCHROETER'S VALLEY	26°	-100°	-100° to -130°				+11 to +49
LITTROW	22°	-98.2°			-82.2 to -99.2	-78.7 to -97.7	-9 to +17

*THESE TRAJECTORIES HAVE THE MIDCOURSE MANEUVER AT TLI +5 HOURS AND MEET A DPS ABORT OF 2000 FPS TWO HOURS PAST PERISELENE.



REPRODUCED FROM REFERENCE 1

FIGURE 1- CONTRAST FOR A LM APPROACH FLIGHT PATH ANGLE OF 15°

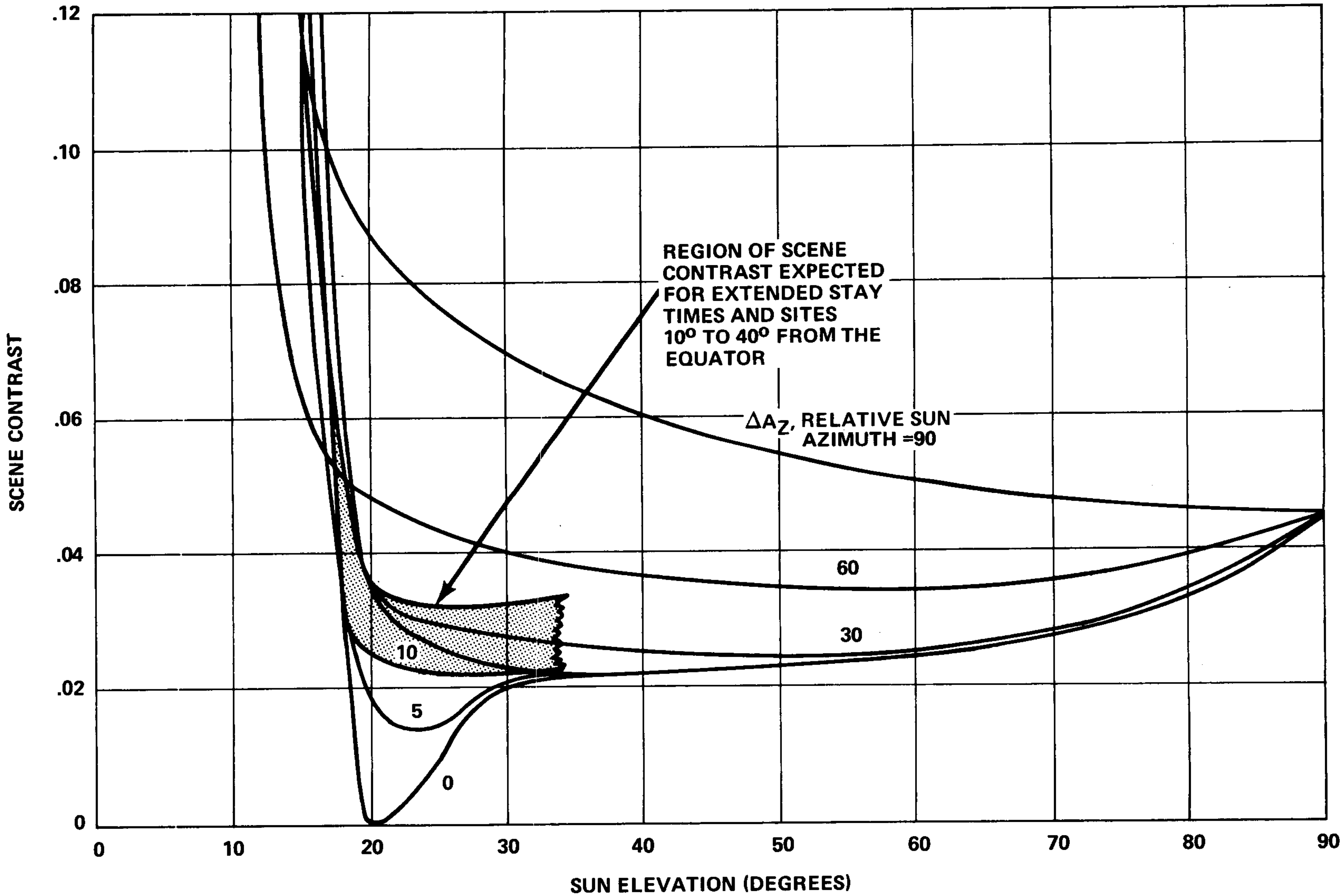


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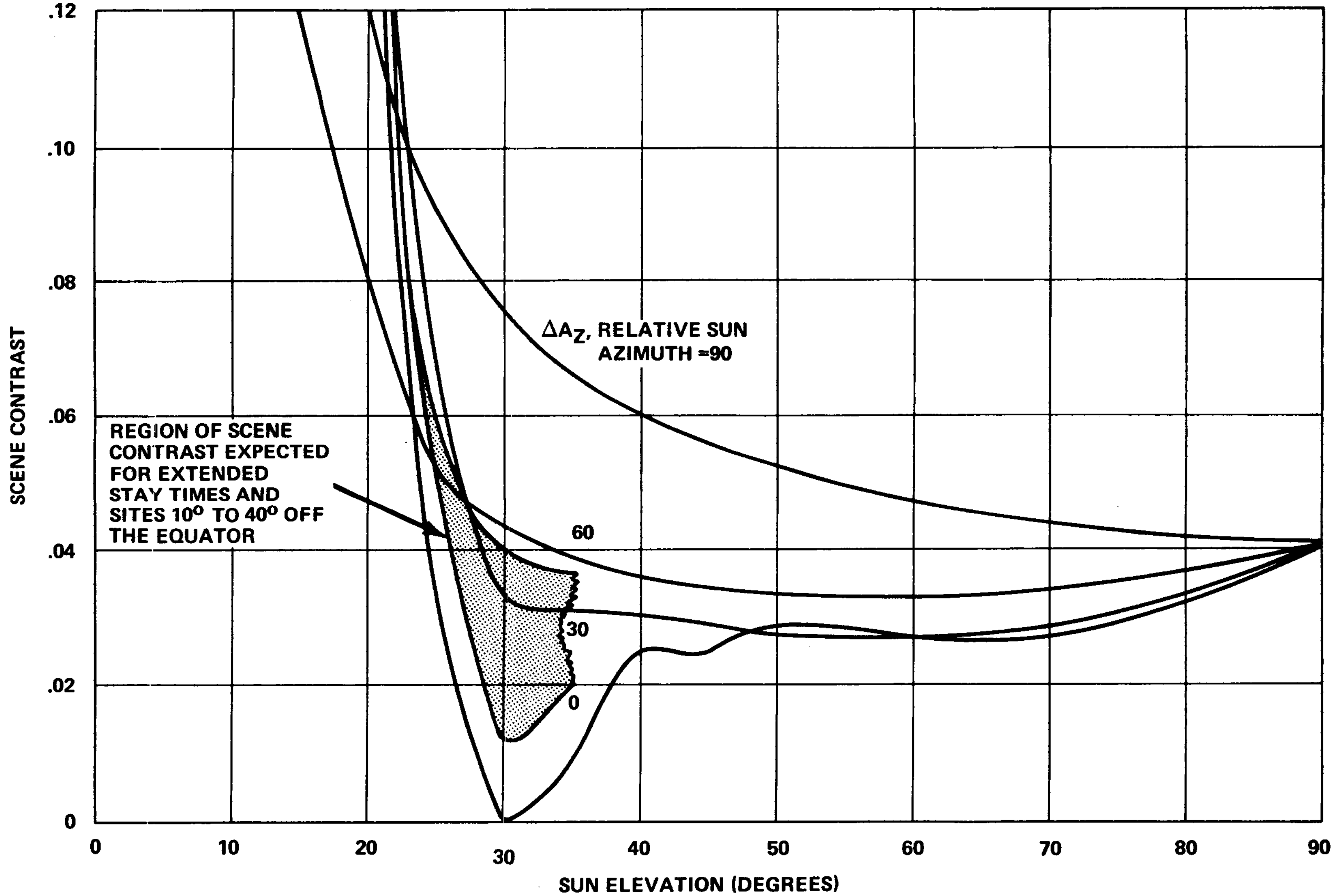
FIGURE 2 - CONTRAST FOR A LM APPROACH FLIGHT PATH ANGLE OF 20°



REPRODUCED FROM REFERENCE 1

FIGURE 3- CONTRAST FOR A LM APPROACH FLIGHT PATH ANGLE OF 30°

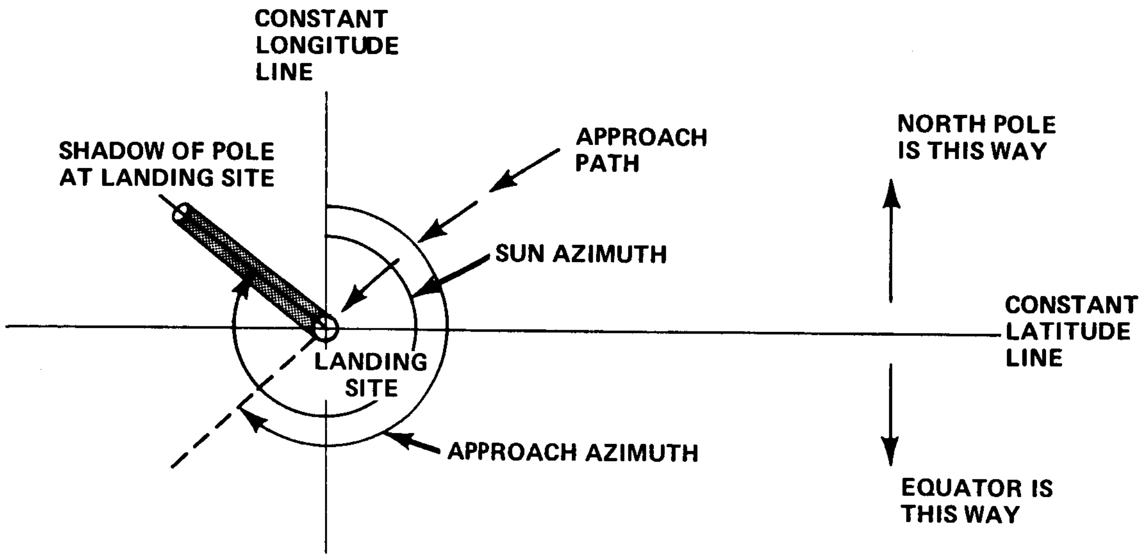


FIGURE 4 - LANDING SITE IN THE NORTHERN HEMISPHERE

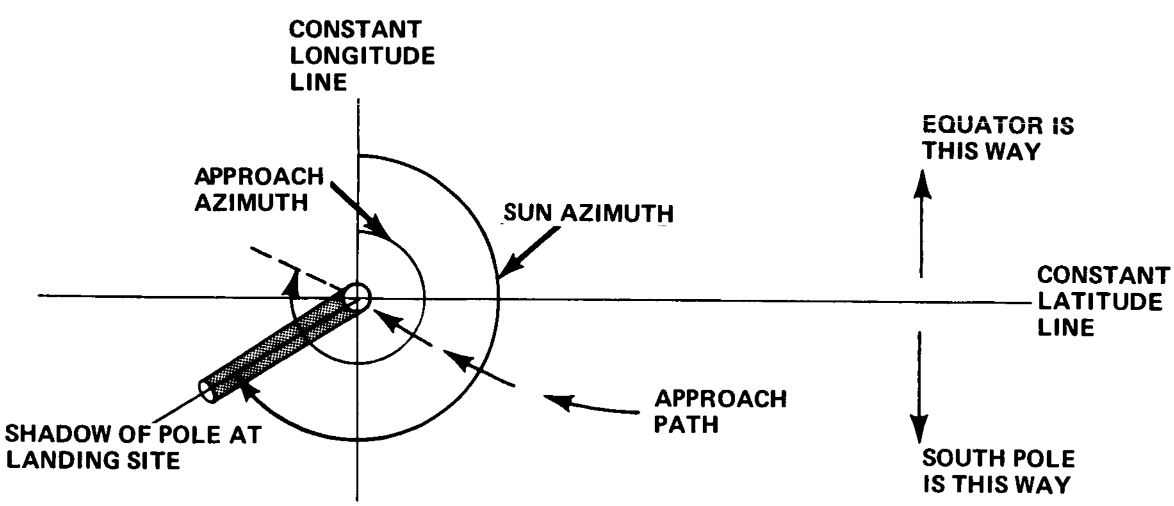


FIGURE 5 - LANDING SITE IN THE SOUTHERN HEMISPHERE

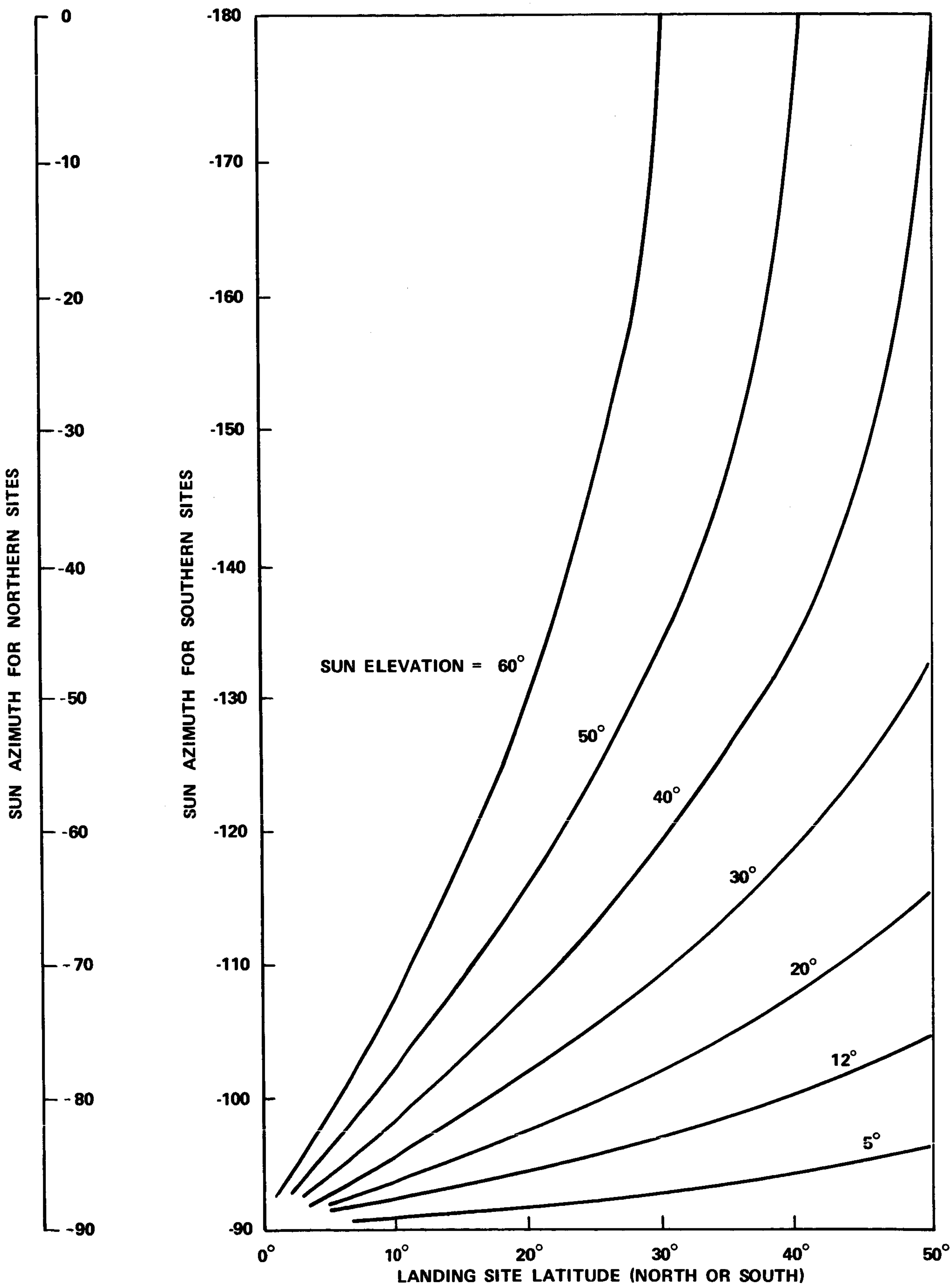


FIGURE 6 - SUN AZIMUTHS AVAILABLE WITH VARIOUS SUN ELEVATIONS AS A FUNCTION OF SITE LATITUDE

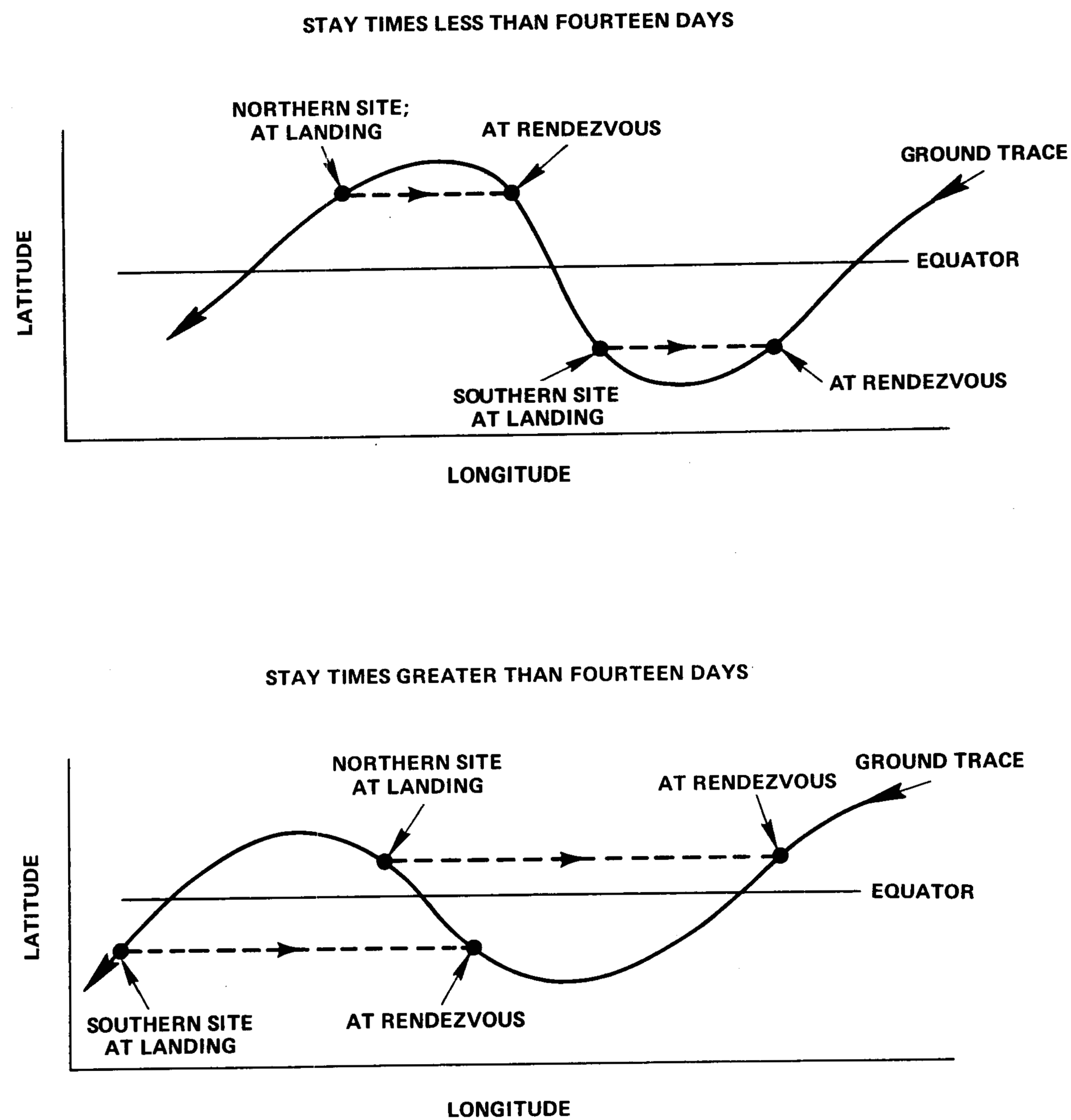

STAY TIMES LESS THAN FOURTEEN DAYS
NORTHERN SITE;
AT LANDING
AT RENDEZVOUS
GROUND TRACE
EQUATOR
SOUTHERN SITE
AT LANDING
AT RENDEZVOUS
LATITUDE
LONGITUDE
STAY TIMES GREATER THAN FOURTEEN DAYS
NORTHERN SITE
AT LANDING
AT RENDEZVOUS
GROUND TRACE
EQUATOR
SOUTHERN SITE
AT LANDING
AT RENDEZVOUS
LATITUDE
LONGITUDE

FIGURE 7 -

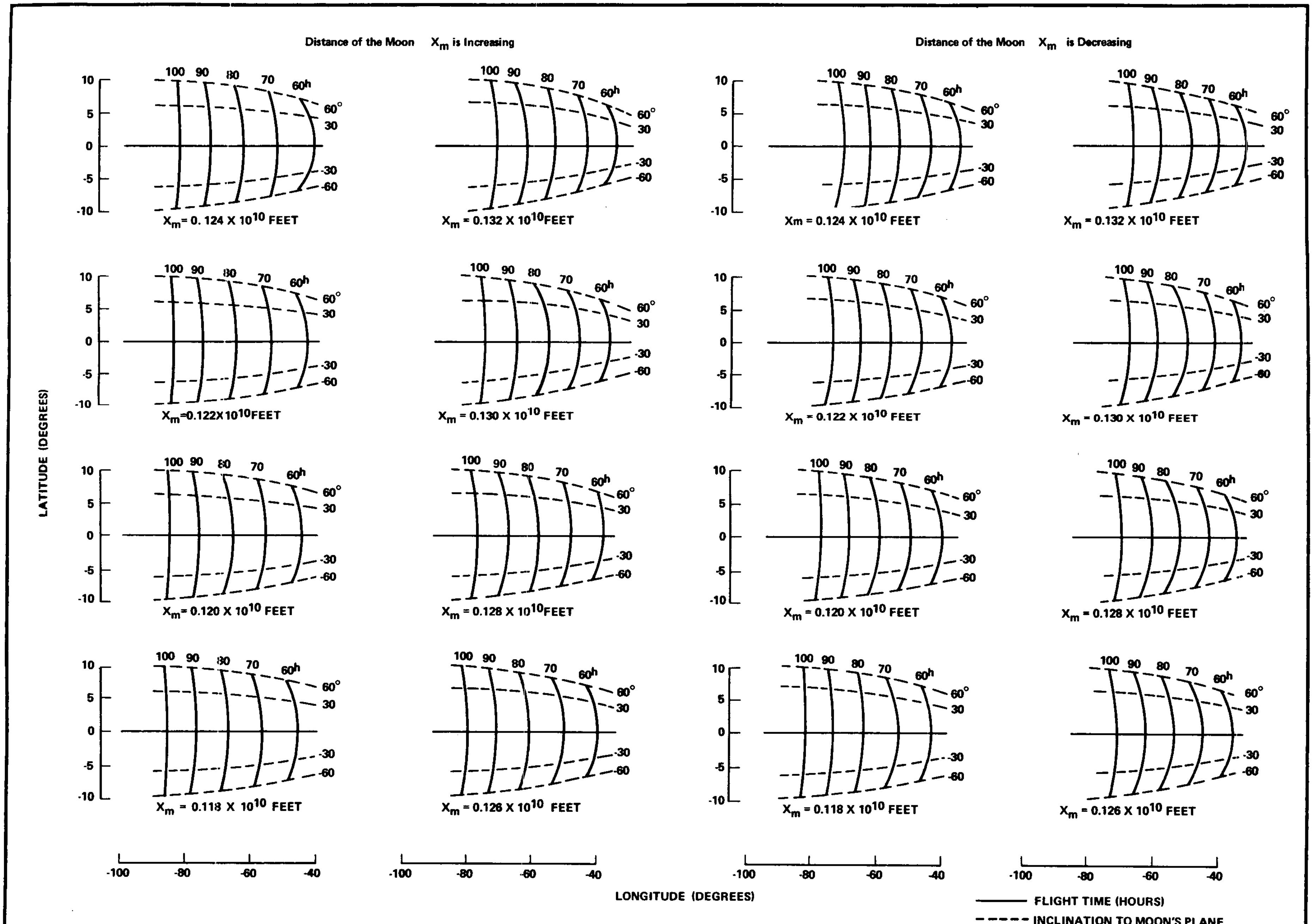
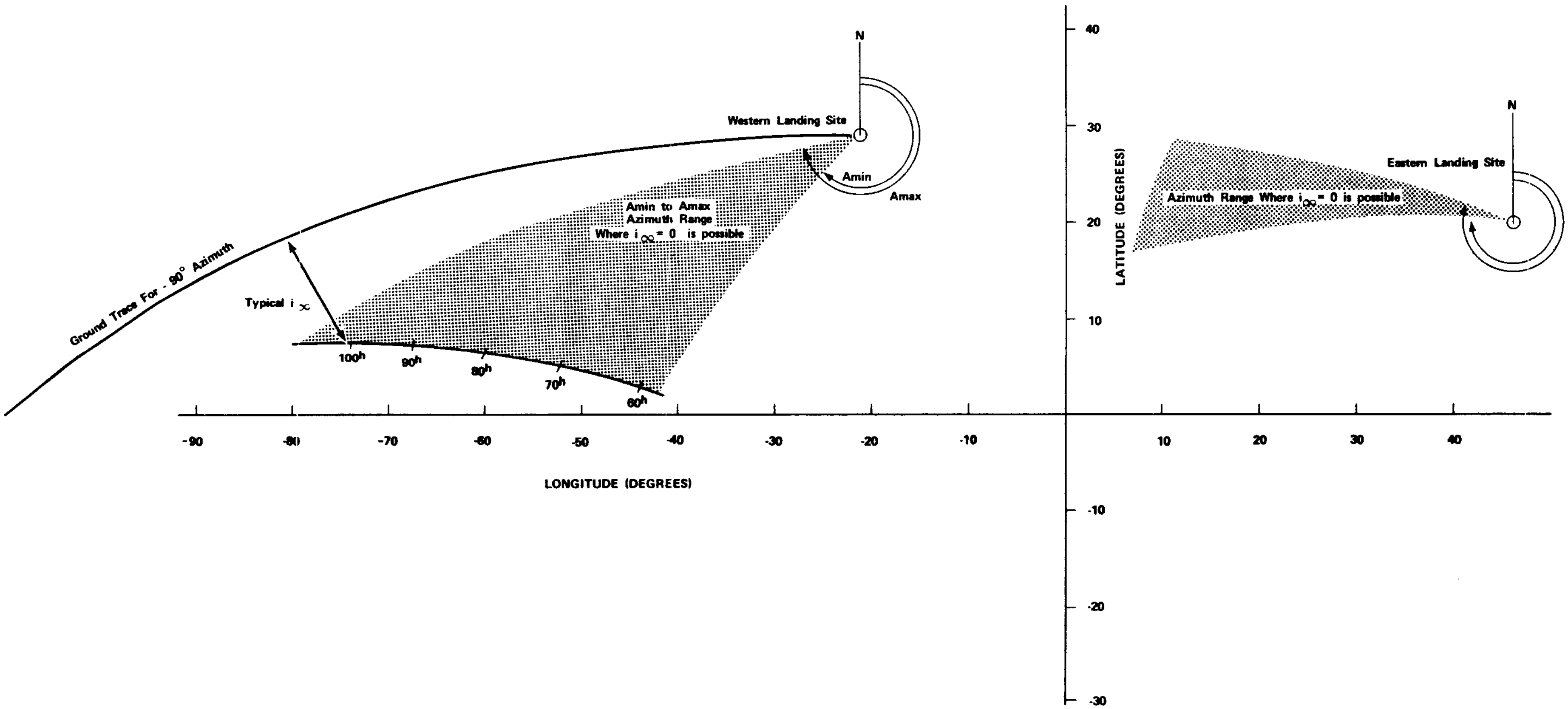


Figure 8 -- Location of the Translunar V_∞ Vectors with Respect to the Moon's Plane.



N
Western Landing Site
Amin
Amax
Amin to Amax
Azimuth Range
Where $i_\infty = 0$ is possible
Typical i_∞
Ground Trace For - 90° Azimuth
100h
90h
80h
70h
60h
N
Eastern Landing Site
Azimuth Range Where $i_\infty = 0$ is possible
LATITUDE (DEGREES)
40
30
20
10
-10
-20
-30
-90
-80
-70
-60
-50
-40
-30
-20
-10
10
20
30
40
LONGITUDE (DEGREES)

FIGURE 9

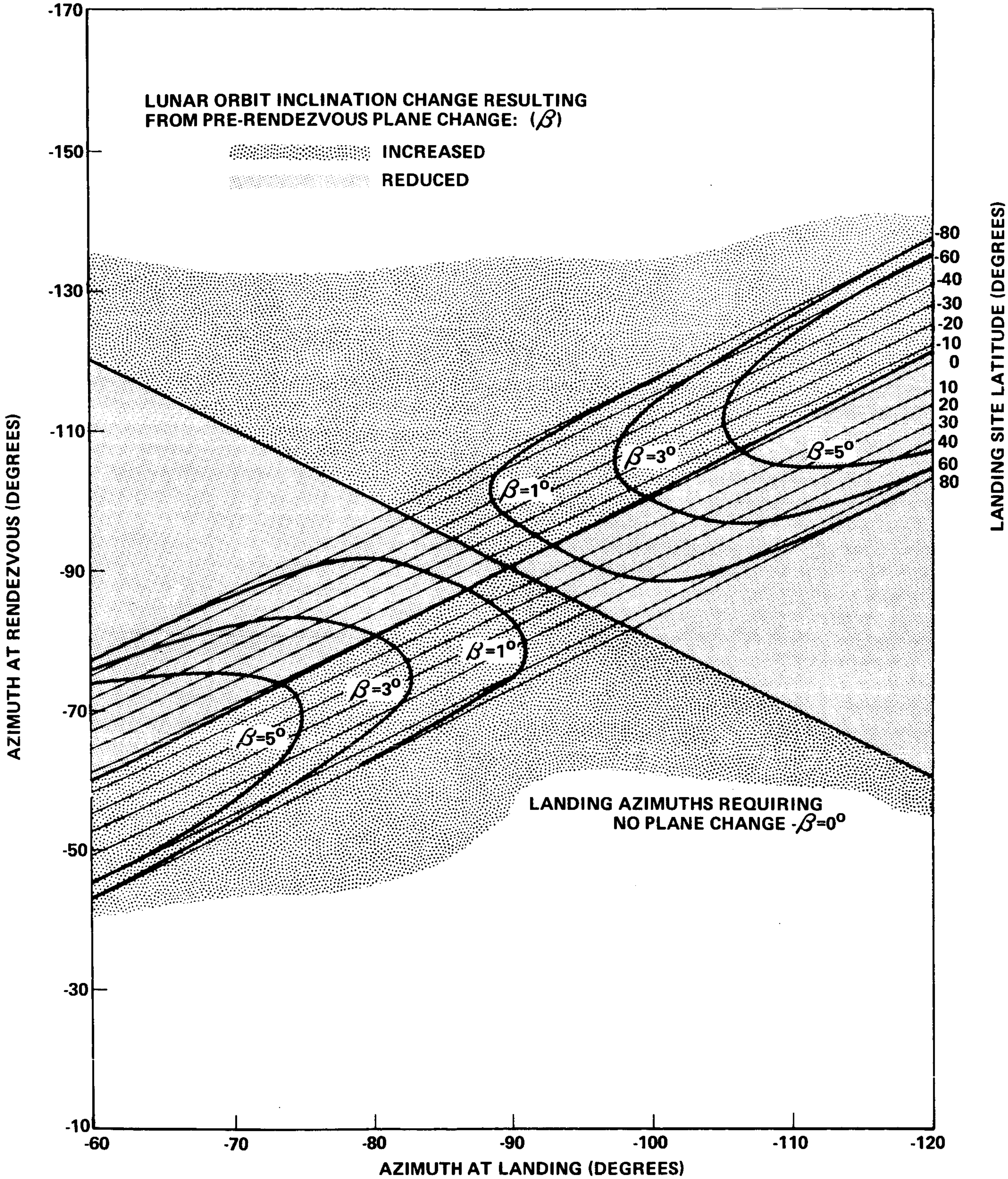


FIGURE 10 - AZIMUTH AT RENDEZVOUS VERSUS AZIMUTH AT LANDING WITH MINIMUM PLANE CHANGE AFTER A 32 HOUR LUNAR STAY TIME

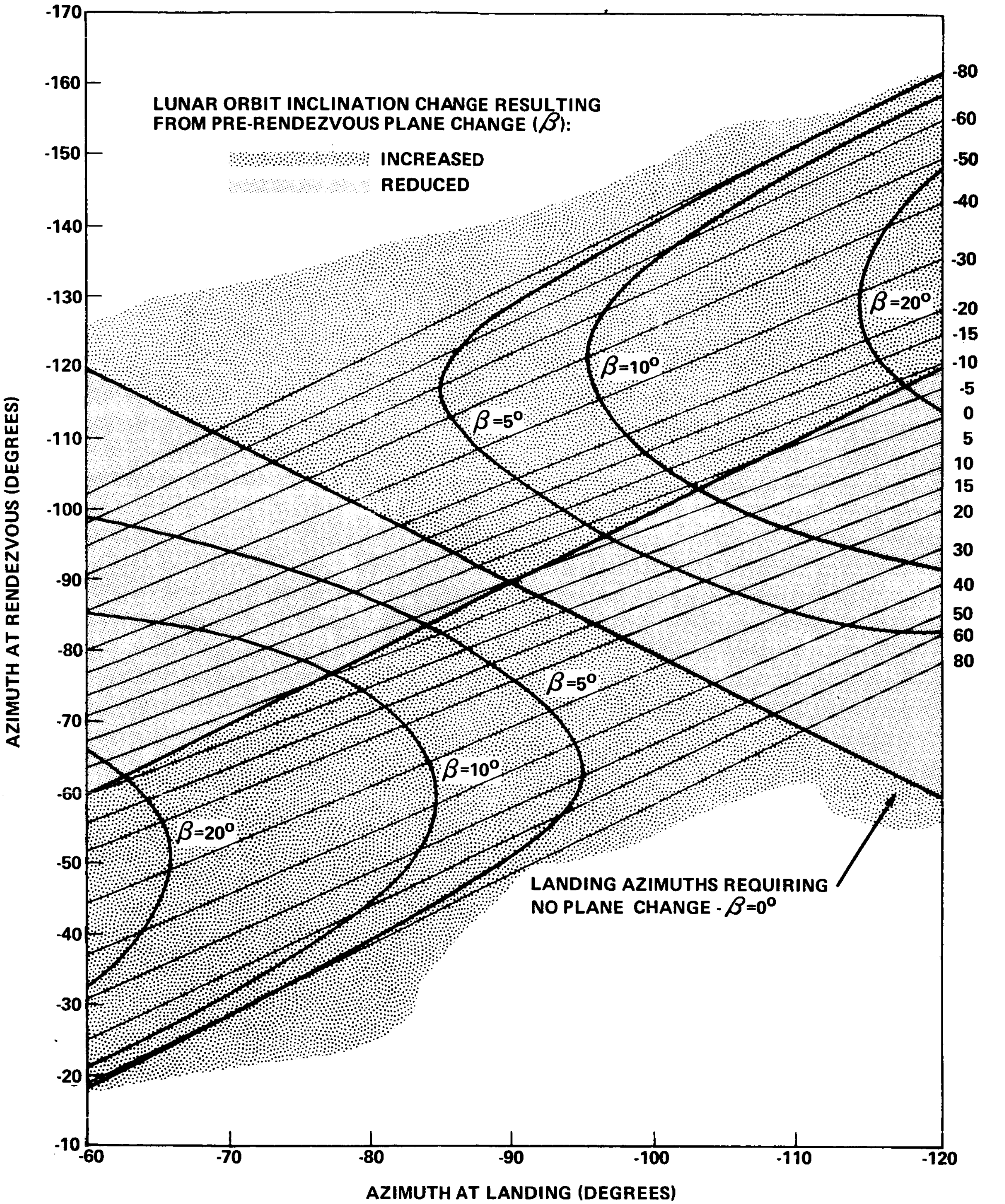


FIGURE 11 - AZIMUTH AT RENDEZVOUS VERSUS AZIMUTH AT LANDING WITH MINIMUM PLANE CHANGE AFTER A 78 HOUR LUNAR STAY TIME

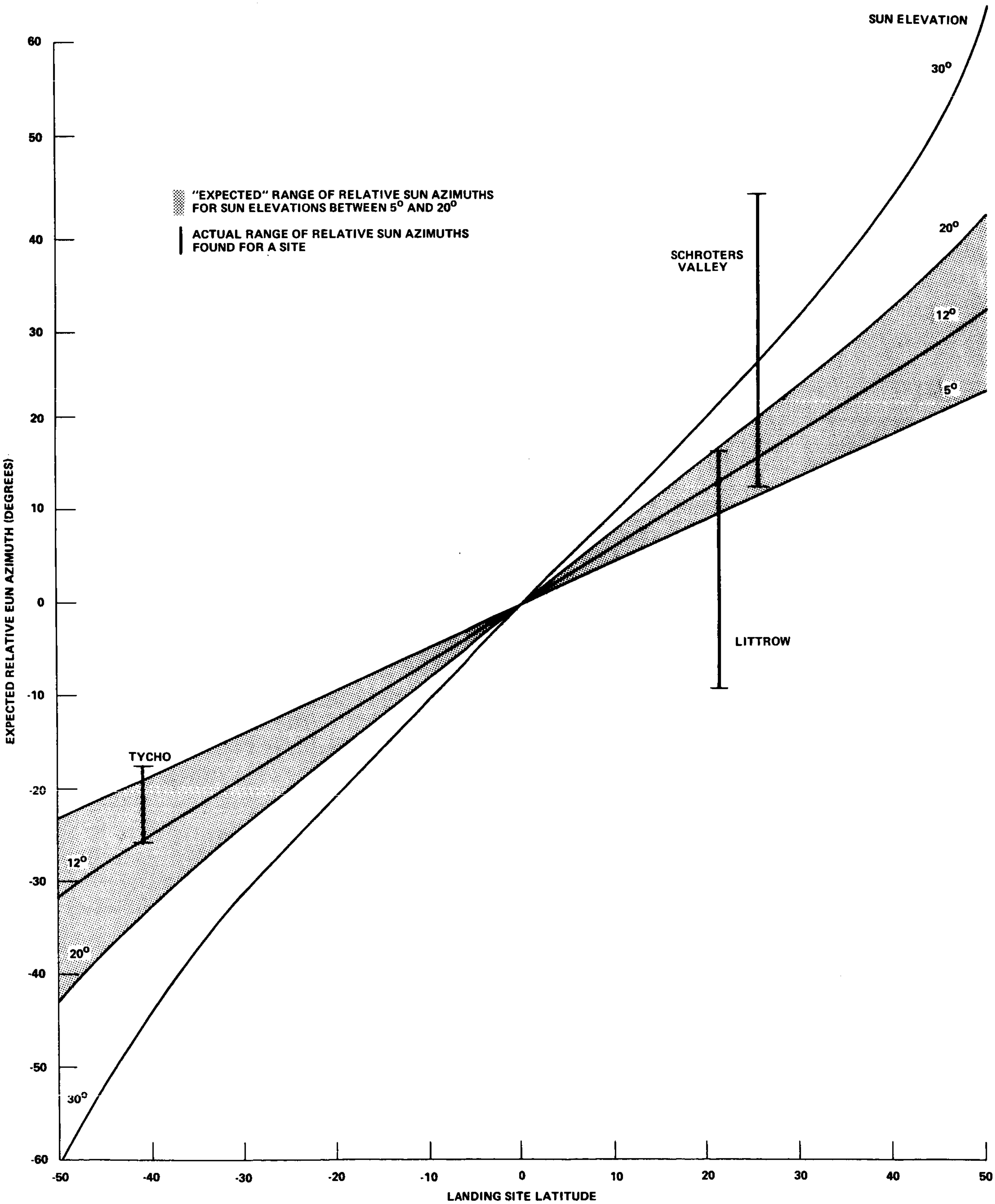


FIGURE 12 - EXPECTED RELATIVE SUN AZIMUTH 78 HOUR STAY TIME

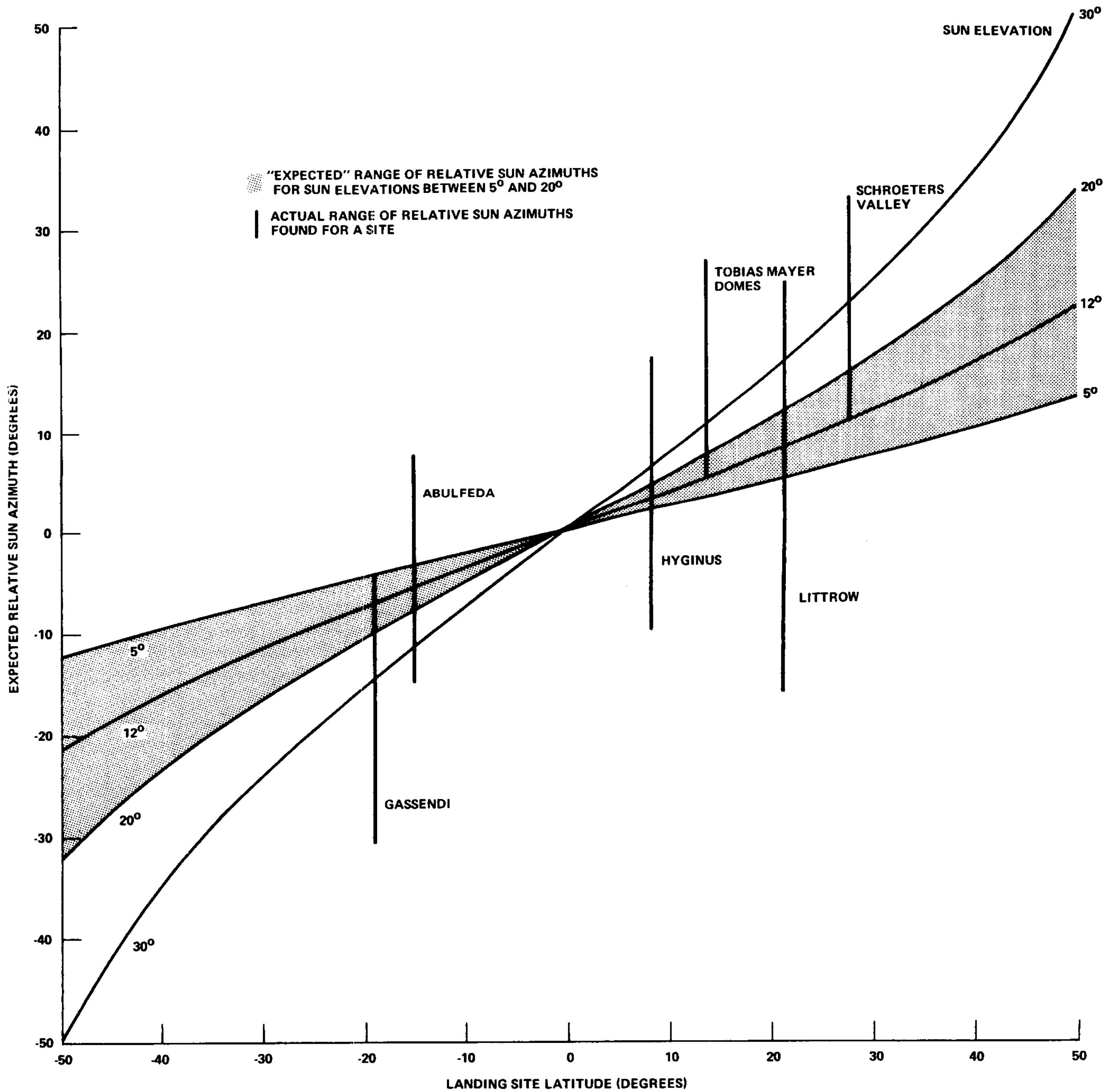


FIGURE 13 - "EXPECTED" RELATIVE SUN AZIMUTH 32 HOUR STAY TIME

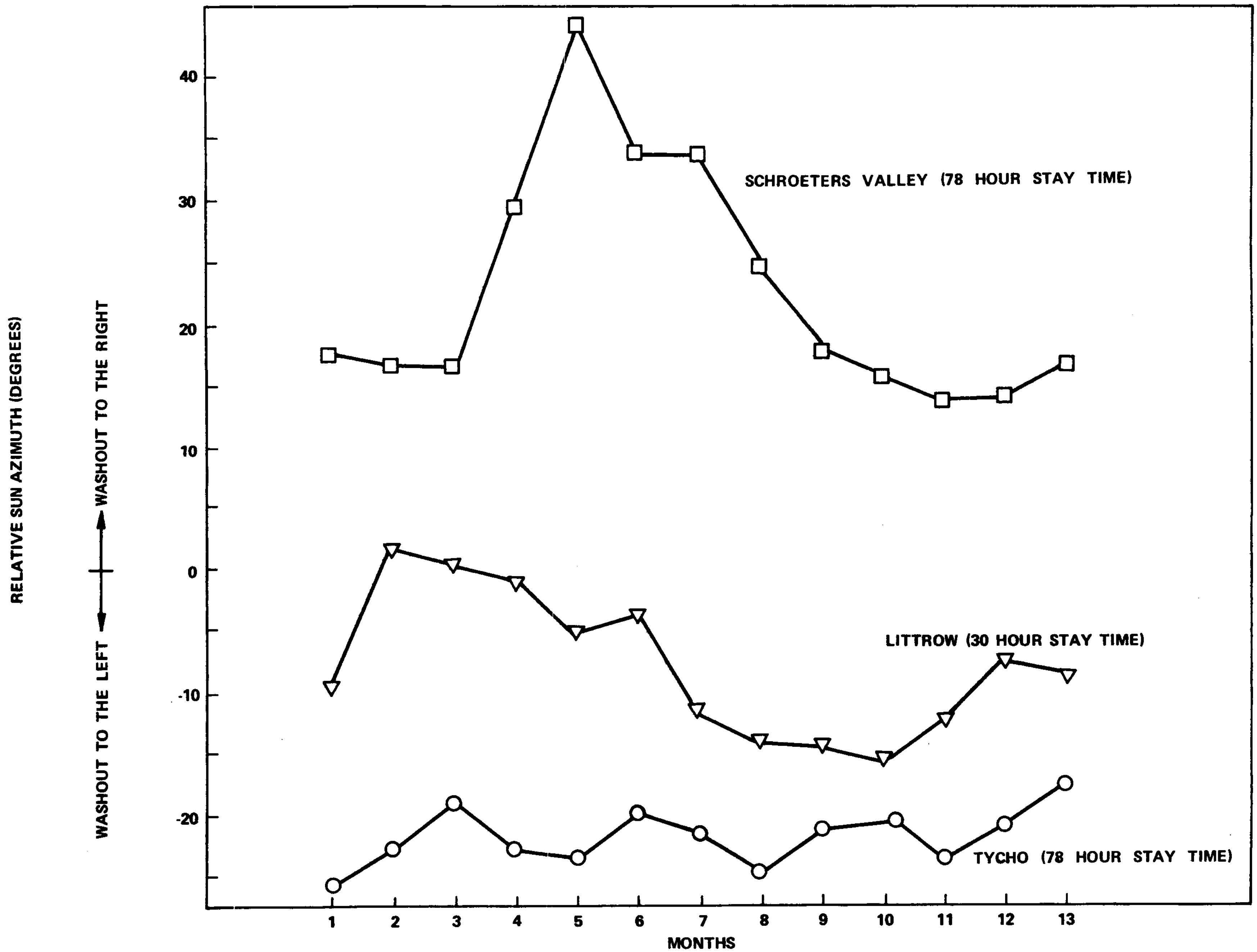


FIGURE 14 - RELATIVE SUN AZIMUTH VARIATION FOR LITTROW, TYCHO, AND SCHROETERS VALLEY THROUGH A LUNAR CYCLE

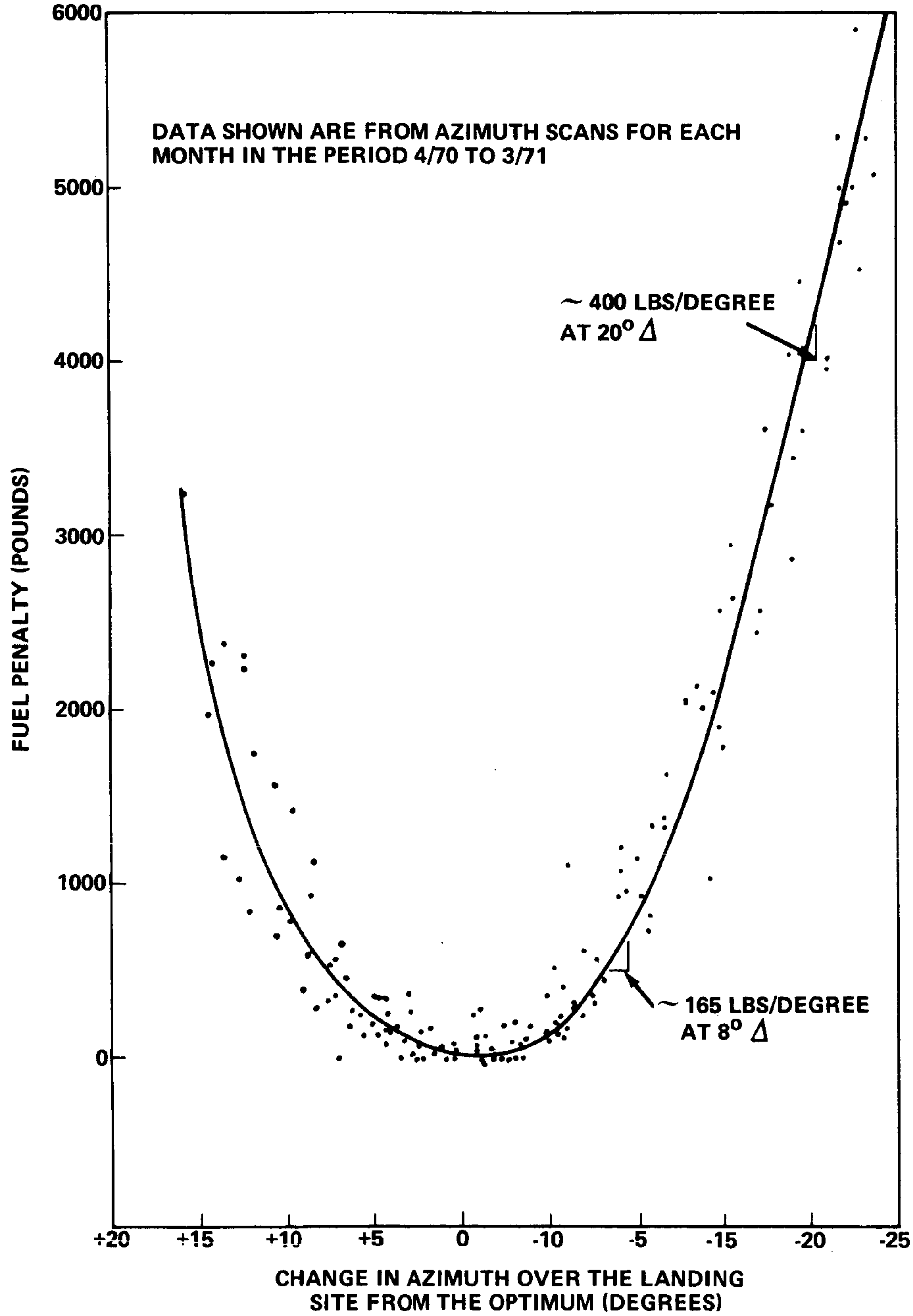


FIGURE 15 - FUEL PENALTY FOR OFF-OPTIMUM AZIMUTHS ACROSS THE LITTROW LANDING SITE

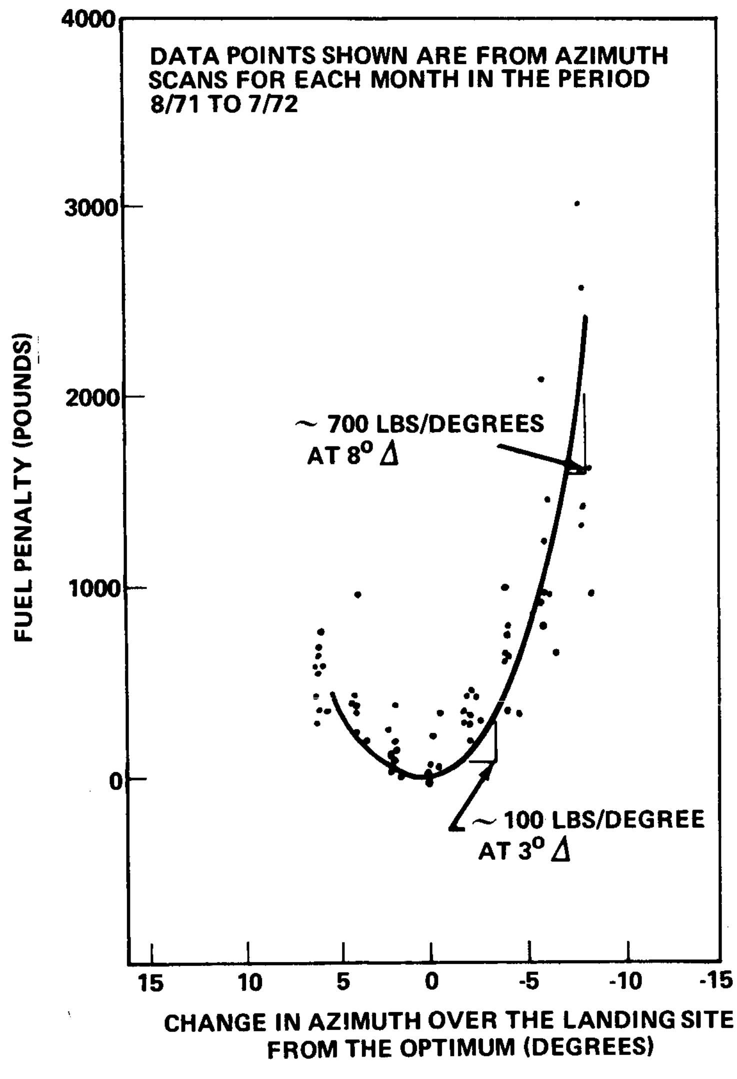


FIGURE 16 - FUEL PENALTY FOR OFF-OPTIMUM AZIMUTHS ACROSS THE TYCHO LANDING SITE

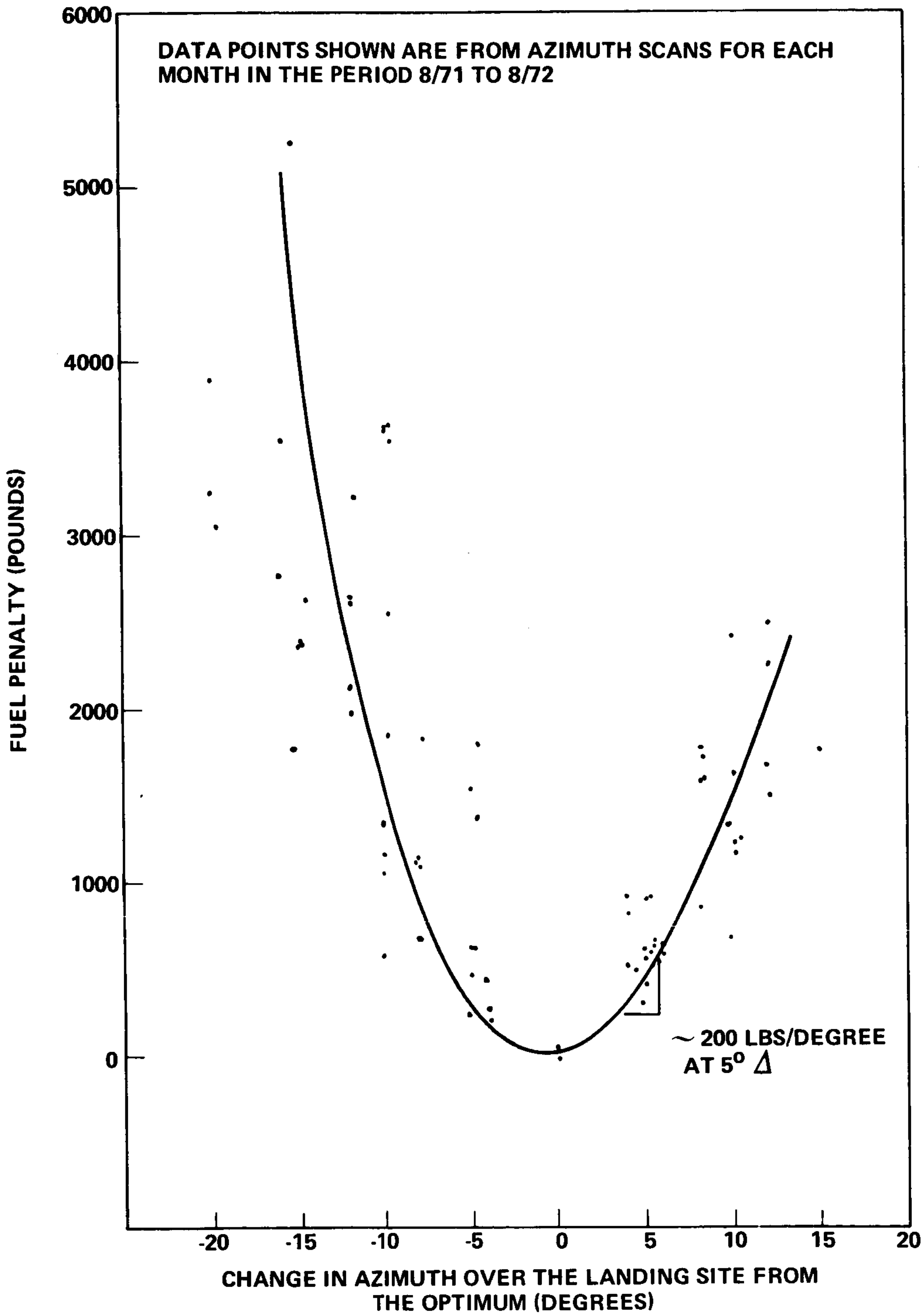


FIGURE 17 - FUEL PENALTY FOR OFF-OPTIMUM AZIMUTHS ACROSS THE SCHROETERS VALLEY LANDING SITE